Rethinking Connections to Accelerate the Construction of Delaware Bridges 1-488 North and South

by Nicholas Dean, Delaware Department of Transportation

For years, the standard Delaware Department of Transportation (DelDOT) practice for connecting adjacent-member bridge superstructures was to use grouted keyways, welded shear connector plates, and post-tensioned tie rods to connect the individual beams in a single unit once they were in place. However, this method of construction caused reflective longitudinal cracking in the decks of many bridges, which led DelDOT to experiment with the use of ultra-high-performance concrete (UHPC) in a revised shear-key shape developed by the Federal Highway Administration (FHWA). DelDOT first used UHPC as part of a bridge replacement project in 2015. Since then, the use of UHPC for the connection of adjacent superstructure elements has been standard DelDOT practice, and numerous projects using the material have been completed.

DelDOT specifications for the UHPC joint mixture require a minimum compressive strength of 17.5 ksi. This minimum-compressive-strength standard is newly adopted and based on guidance from FHWA's 2023 report *Structural Design with Ultra-High Performance Concrete*.[1] Because of DelDOT's continued commitment to the use of UHPC, precast concrete producers in the surrounding region have invested in reusable formwork for the superstructure shear key (longitudinal joints). While reusable formwork represents a significant upfront cost for the fabricator, it is also a huge step toward normalizing the use of UHPC.

The replacement of two bridges (1-488N&S) over Blackbird Creek along US 13 in northern Delaware was an opportunity to further refine UHPC practices. The successful use of the decked bulb-tee superstructure and precast concrete approach slabs for Bridges 1-488N&S was heavily predicated on the use of UHPC for the joints. Without UHPC, the closure pours and formwork for the joints would have been much larger and involved much more labor. Additionally, reflective cracking would have likely occurred if UHPC were not used. (For more information on the Bridges 1-488N&S over Blackbird Creek project, see the Project article on page 14.)

UHPC Decked Bulb-Tee End-Diaphragm Joints

The precast, prestressed concrete decked bulb-tee beams used for the Bridges 1-488N&S over Blackbird Creek project have large precast concrete end diaphragms that function as the backwall and seats for the precast concrete approach slabs. Because of the complexity of these types of diaphragms, it is common to field-cast them.

Crew members work on the top forms for the longitudinal ultra-high-performance concrete (UHPC) shear key joints. The system of top forms and buckets filled with UHPC creates a pressure head and forces UHPC into all of the voids within the joint. All Photos: Delaware Department of Transportation.

A close-up view of the approach slab joint showing the noncontact lap splice between the precast concrete elements. Backer rod is used to create a watertight seal and prevent ultra-high-performance concrete leakage.

However, given the time constraints of the project, the end diaphragms were precast integral with the beams and connected transversely with UHPC at the jobsite. In Delaware, placement of the entire joint in a single operation is preferred, but the contractor expressed concerns that the time needed to obtain appropriate UHPC strengths would affect the timing of other operations. Therefore, instead of holding up other operations while the contractor prepared formwork for the longitudinal shear key joints of the beams, the UHPC for the end diaphragms was placed separately, before that of the longitudinal joints.

The contractor also collaborated with the precast concrete producer during the shop drawing phase to address challenges related to the complexity of the joint and the limited space around the end diaphragms. The team decided to have threaded inserts installed on the underside of the end-diaphragm joint and back of the end diaphragms to facilitate placement of the formwork for the UHPC. In advance of the UHPC placement, the contractor's carpenters prepared the forms. After the beams were set, the threaded inserts and precut forms allowed the contractor to quickly prepare for the UHPC placement. The end-diaphragm joints required vertical placement of the UHPC, so the watertight integrity of the joints was even more important than usual. The formwork for the end-diaphragm joints consisted of ¾-in.-thick, 10-in.-wide lengths of plywood to cover the 6 in. joint width. On each side of the plywood formwork, ½-in.-thick foam expansion material was attached for the entire length of the joint. Tie rods were then threaded into the inserts and used to secure the plywood to the end diaphragms. By sufficiently tightening the nuts on the tie rods, the crews were able to compress the strips of foam expansion material and create a watertight seal. Because the UHPC in the longitudinal beam joints would be placed later, bulkheads were installed between the end diaphragm and the longitudinal beam joint.

Placing the UHPC for the joints of the end diaphragms required roughly 5 yd^3 per bridge. All the work associated with the UHPC end-diaphragm joint placement was performed over four days: one day per bridge to prepare the surface and install formwork, and approximately 1.5 hours of UHPC placement per bridge. To achieve a saturated surface dry (SSD) condition for the surface, the contractor used soaker hoses and wet burlap in the joints the day before the UHPC was placed. This preparatory step allowed the internal pores of the precast concrete joint to absorb the moisture from the soaker hoses and wet burlap, and kept the precast concrete from pulling the water out of the UHPC.

Watertight formwork on the backside of the beam for the ultra-high-performance concrete (UHPC) placement in the end diaphragm joints. A series of threaded inserts, ½-in.-thick foam, tie rods, and plywood are used to ensure that no UHPC is lost due to leakage.

Workers place ultra-high-performance concrete (UHPC) from a concrete hopper into a longitudinal joint between adjacent decked bulb-tee beams. After the UHPC is placed, the joint is top formed and a pressure head system is created.

The timing of the backfilling operations for the foamed glass aggregate (FGA), as well as construction of the temporary walkways outside of the bridge parapets, was dependent on achieving adequate strength in the UHPC. Backfilling against the abutments and attaching the overhang brackets and walkways to the beams required that the UHPC reach a compressive strength of 10 ksi. It took the UHPC approximately two to three days to gain the required strength. By sequencing the UHPC placement operations, the contractor was able to give the UHPC in the end-diaphragm joints a head start on gaining strength while crews worked to assemble the formwork for the longitudinal joints. This sequencing allowed the other construction operations to continue alongside the UHPC placement for the longitudinal shear keys.

UHPC Decked Bulb-Tee Shear Key Joints

For the longitudinal joint formwork, lengths of 2× lumber were placed across the 6 in. joint width. As was done for the end-diaphragm joints, ½-in.-thick foam expansion material was attached to each side of the lumber, and tie rods

End diaphragms are typically cast-in-place because of their complexity. However, given the time constraints of this project, the end diaphragms were precast integral with the beams and connected transversely with ultra-high-performance concrete at the jobsite.

were used to pull the bottom form tight against the underside of the beams and create a watertight joint. This approach with the formwork is something that the contractor developed and fine-tuned over the course of two other DelDOT bridge construction projects involving UHPC. By paying close attention to detail with the formwork, the contractor was able to avoid losing UHPC from the longitudinal joints.

Approximately 16.5 yd³ of UHPC per bridge was placed for the longitudinal joints. All the work associated with the longitudinal UHPC joint placement was performed over six days: two days per bridge to prepare the surface and install formwork, and approximately four hours per bridge to place the UHPC.

During the UHPC installation in the longitudinal joints, the contractor elected to try two different techniques. The first followed common DelDOT practice for a 6 in. joint with a UHPC closure pour. UHPC was placed into troughs to help guide the materials into the joint. These troughs were moved along the beams from low to high elevation. As the UHPC was placed in the joint, a top form composed of ¾-in.-thick, 10-in.-wide lengths of plywood was applied. As was done for the formwork for the end diaphragm, ½-in.-thick foam expansion material was attached for the entire length of the joint. Concrete screws were drilled into the top edges of the precast concrete decked bulb-tee to cinch the plywood and expansion material down tight. At tenth-points along the beam, crews attached buckets with holes drilled into the bottom to the joint. These buckets were filled with UHPC and created a pressure head system, forcing the viscous material into any open void within the joint. As the UHPC placement progressed, the buckets were continuously topped off to maintain the pressure head.

This tried-and-true technique has worked on many DelDOT bridge construction projects in the past. When compressed, the foam expansion material maintains approximately ¼ in. of UHPC overpour in the joint. This hardened overpour is then ground flush with the top of the precast concrete element. The advantage of using this approach is that it helps ensure that UHPC fills every void and limits the potential for low spots in the joint. The drawback is that the work to top-form the longitudinal joint requires a significant amount of time, personnel, and effort.

For a portion of the concrete placement for the longitudinal joint on Bridge 1-488N, the contractor used a different UHPC placement technique: installing the product without top forming the joints. This option was suggested by a representative for the UHPC supplier, and the contractor decided to try it because it could potentially save time during the UHPC placement process; however, they were aware that there could be a greater likelihood of low spots developing in the joint because of underpouring.

In practice, this method did not yield the desired advantages. Because of the slope of the beams, the self-consolidating UHPC gravitated toward the low point and overflowed the joint. Notably, the contractor expressed the belief that this method could be feasible under the right conditions. However, given the time frame for completing the project, the contractor returned to the more conventional UHPC placement technique.

UHPC Approach Slab Shear Key Joints

After the UHPC was placed for the decked bulb-tee beams, the contractor placed the precast concrete approach slab segments. The use of fully precast concrete approach slabs was made possible because of the strength and durability that the UHPC connection can provide. For this project, the joints between the approach slab segments were designed to match FHWA's shear key for adjacent box beams. Because this shear key is only ⅜-in. wide, the contractor was able to use backer rod in lieu of wooden formwork.

Adjacent decked bulb-tee beams are staged in the precaster's yard. The backsides of the beams show the threaded inserts for the ultra-high-performance concrete (UHPC) formwork. The reinforcement configuration creates a noncontact lap splice in the UHPC joint between beams.

An adjacent decked bulb-tee beam is staged in the precaster's yard. The precast concrete interface that will form the side of the longitudinal joint has a roughened concrete surface and reinforcement that will project into the joint to help the UHPC bond to the precast concrete beam.

The slope of the approach slabs on the north side of the bridges is ±0.5%, while the slope is ±2.5% on the south side. Learning from the experience with the UHPC placement on the longitudinal beam joints, the contractor implemented a hybrid technique of top forming the southside approach slab joints and open placement of the northside approach slab joints. Approximately 1.5 yd^3 of UHPC per bridge was placed in the joints of the approach slabs. All work associated with placement of the UHPC approach slab joints was performed over three days: one day per bridge to prepare the surface and install formwork, and approximately 1.5 hours of UHPC placement per bridge.

UHPC Mixing and Delivery Method

The UHPC for Bridges 1-488N&S was mixed off site, at a concrete plant. This was a new mixing and delivery method for UHPC in Delaware.

On previous UHPC projects, the material was mixed on site with high-energy, high-shear mixers. That on-site process adds several layers of complexity to bridge projects, such as the following:

- Many bridge replacement/rehabilitation projects have relatively small footprints. As such, staging of the mixers, batch materials, and UHPC delivery systems can become a major concern.
- When UHPC is mixed on site, the number of personnel on site increases signifcantly. Depending on the size of the UHPC placement, it is not uncommon for the contractor to allocate 20 to 25 people for mixing UHPC, delivering material from the mixers to the joints, assembling and installing top forms, topping off pressure head buckets, ensuring joint integrity, and general quality assurance/quality control processes.
- The success of UHPC placement depends on efficient delivery and installation of materials, whereas an interruption to on-site mixing operations can result in loss of material, the need for remedial actions, and the derailment of tight construction schedules. On UHPC projects in Delaware, it is common for mixers to malfunction. Therefore, DelDOT requires a minimum of two high-energy, high-shear mixers for every UHPC project, regardless of the size of the placement project.

With so many moving parts created by on-site mixing of UHPC, the risk of inefficiency and waste increases significantly.

For the Bridges 1-488N&S project, the UHPC material supplier trained and certified members of the local concrete supplier to mix the material using standard mixers. Using typical mixing machines allows for a level of control that cannot easily be achieved in the field. Additionally, training concrete plant staff in the nuances of UHPC helps them understand the material and troubleshoot any issues that could arise in production. Also, with this off-site mixing process, larger quantities of UHPC can be mixed in a single batch.

For this project, representatives from the UHPC supplier and DelDOT's Materials & Research section oversaw the mixing process at the plant. The mixing process took approximately 1.5 hours to complete. Once the UHPC was mixed, testing samples were taken, and the UHPC was loaded into a standard ready-mix truck. It then took another 30 minutes to deliver the material to the construction site. The mixing barrel on the concrete truck slowly rotated, and as a result, the UHPC remained workable for approximately 4 hours.

Once the UHPC was on site, it was loaded into a concrete hopper, which was lifted by crane and smoothly guided along the joints, quickly filling them with UHPC as it went. The concrete hopper, which had a capacity of 2 yd^3, had a spring gate that allowed the trained workers to easily control the flow of UHPC. On-site mixing procedures typically use wheelbarrows or concrete buggy machines during placement. That equipment offers a capacity of between 6 and 14 ft^3, which is only about 10% to 25% of the capacity of the concrete hopper. Use of the concrete hopper eliminated the need for wheelbarrows and buggies, and a smaller crew was easily able to place the UHPC, install top forms, maintain the pressure head system, and ensure joint integrity. The decreased site congestion increased the speed and efficiency of the UHPC placement process. It also improved the cleanliness of the construction site compared with an on-site UHPC mixing operation.

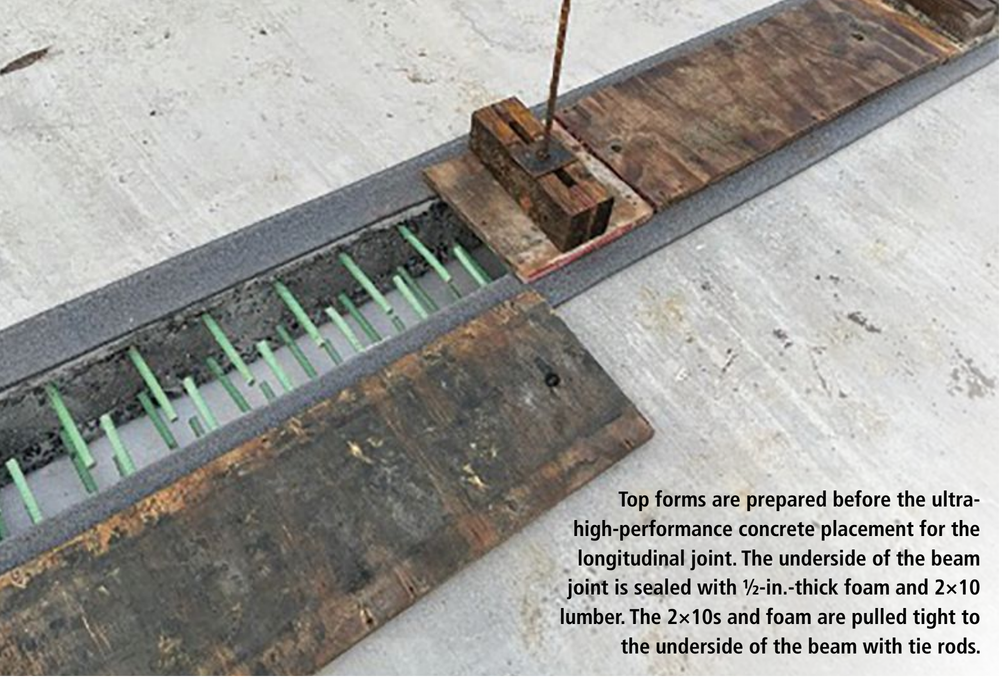
Conclusion

Some of the UHPC lessons learned from the replacement of Bridges 1-488 N&S are as follows:

- It is vital to have a contractor that is experienced in and open minded about the use of UHPC. The contractor for this job is one of Delaware's more knowledgeable UHPC installers. They continue to look for ways to improve delivery and implementation of the material, and they are open to suggestions throughout the construction process.
- Care should be taken when sealing the beams and building the formwork for UHPC placement. The contractor's formwork approach helped accelerate placement and eliminate UHPC leakage.
- Mixing UHPC off site eliminates the need for large mixers within the work zone, allows for larger UHPC batches, and provides an added level of quality control. It is important for

concrete plant staff to be trained and certified in the UHPC mixing process, and it is also recommended that a supplier's representative be present for oversight.

- As noted by the contractor, material waste can be a concern during the off-site mixing of UHPC. The concrete plant that mixed the UHPC was only set up to batch the material in increments of 1 yd^3. If smaller increments were achievable, that could help to reduce material waste. This issue might be resolved as this process becomes more mainstream and concrete plants adjust their procedures.
- Eliminating top forms may help speed up UHPC installation, but it is important that slopes are considered. The contractor found success when no top forms were used on flatter joints but encountered difficulties with this technique on slopes greater than 0.5%. With more time and planning, steps could be taken to mitigate issues on joints with steeper slopes.



Top forms are prepared before the ultra-high-performance concrete placement for the longitudinal joint. The underside of the beam joint is sealed with ½-in.-thick foam and 2×10 lumber. The 2×10s and foam are pulled tight to the underside of the beam with tie rods.

- Using a concrete hopper improved the speed and efficiency of UHPC installation. It also decreased the number of personnel required for the operation and minimized site congestion.
- Off-site UHPC mixing and delivery of UHPC in ready-mix trucks improve the efficency of UHPC installation. Given the merit to this approach, it is likely that more UHPC suppliers will modify their mixture proportions to suit this method, leading to more concrete plants becoming proficient in mixing UHPC and further advancement of the industry.

By combining precast concrete elements with refined shear key joints and improved UHPC delivery methods, DelDOT expects that the new bridges over Blackbird Creek will have a 100-year design life with minimal maintenance.

Reference

1. Graybeal, B., and R. El-Helou. 2023. *Structural Design with Ultra-High Performance Concrete*. FHWA-HRT-23-077. Washington, DC: Federal Highway Administration. https://rosap.ntl.bts.gov/view/dot/72525.